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A calibration and temperature correction procedure for the water-content reflectometer

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Abstract

Calibration is required for most soil moisture sensors if accurate measurements are to be obtained. This can be time consuming and costly, especially if field calibration is undertaken, but can be facilitated by a good understanding of the behaviour of the particular sensor being calibrated. We develop generalized temperature correction and soil water calibration relationships for Campbell Scientific CS615 water-content reflectometer sensors. The temperature correction is estimated as a function of the raw sensor measurement. The calibration relationship requires one soil-related parameter to be set. These relationships facilitate field calibration of these sensors to acceptable accuracies with only a small number of samples. Copyright © 2005 John Wiley & Sons, Ltd.

Key Words   soil moisture; water content reflectometer; calibration

Introduction

Soil moisture (θ) measurements can be achieved using a variety of approaches. A common approach is to measure changes in the soil dielectric constant, which makes use of the contrast between the dielectric constant of air (1), soil mineral particles (3–7) and liquid water (approximately 80). Time-domain reflectometry (TDR) is widely used to measure soil dielectric constant, from which θ can be inferred. TDR calibration relationships are quite stable to variations in soil type, and well-known general calibration relationships exist, e.g. the Topp equation (Topp *et al.*, 1980), although calibration relationships for soils with large clay and or organic matter content can vary significantly from these general relationships (Hook and Livingston, 1996). TDR also has an advantage in that it has a low sensitivity to soil temperature (Pepin *et al.*, 1995).

TDR instruments are expensive and rely on analysis of measured waveforms, which may be problematic (Logsdon, 2000). A range of cheaper devices relying on measuring a response to changes in the bulk soil dielectric constant have been developed in recent years. These instruments generally operate at much lower frequencies (10–100 MHz) than TDR (700–1000 MHz) and, as a consequence, are more sensitive to variations in soil properties and temperature (Seyfried and Murdock, 2001, 2004). In fact, temperature sensitivity is a universal, sometimes very large, problem for non-TDR dielectric sensors, and independently

tested correction approaches are rare or nonexistent in the literature. Also, it is generally necessary to calibrate these sensors for specific soils if actual measurements of θ are required, as opposed to some indication of soil water fluctuation over time. This paper summarizes temperature correction and calibration methods developed and tested with one particular sensor, the Campbell Scientific CS615 water-content reflectometer (Campbell Scientific Inc., 1996), which is a transmission line oscillator that operates in the time domain like TDR but at a lower frequency (Kelleners *et al.*, 2005).

The CS615 consists of a printed circuit board connected to two parallel stainless steel rods that act as wave guides. The rods are 3·2 mm in diameter, 300 mm long and are separated by 32 mm. A robust version of this sensor with rods 200 mm in length is also available, but is less commonly used. The circuit forms a bistable vibrator producing pulses that travel along the wave guides and reflect off the open end. The maximum incident wave frequency (propagating into the soil) is 45 MHz (Kelleners *et al.*, 2005). This oscillation frequency of the circuit is sensitive to the dielectric constant and electrical conductivity (EC) of the bulk soil. The oscillation frequency signal is scaled down to about 1 kHz and the sensor output is a square wave with $\pm 2 \cdot 5$ V amplitude, the frequency or period of which can be recorded with a data logger. In this paper we follow Campbell Scientific Inc. (1996) and Seyfried and Murdock (2001) and use measurements of the period produced by the CS615 as the sensor signal.

Recently, Campbell Scientific has released an updated version of this sensor, the CS616. Although the specific relationships developed in this paper are not applicable to this new sensor, we believe the approach is applicable because the CS616 uses the same operating principle, but at a somewhat higher measurement frequency (maximum measurement frequency approximately 175 MHz compared with 44 MHz; Kelleners *et al.*, 2005). Like the CS615, the CS616 also shows marked sensitivity to soil type and temperature. Thus, although some recalibration or refitting of the equations would be necessary to apply the approach to the CS616, we believe that the benefits in terms of facilitating easier field calibration will also exist for the new sensor.

The sensitivity of the CS615 calibration to soil type and temperature relative to TDR is largely explained by the differing measurement frequencies. The CS615 measured period is a function of K^*, the complex dielectric constant of the soil:

$$K^* = K' - iK'' \tag{1}$$

where K' and K'' are the real and imaginary components respectively of the complex dielectric constant. The K' values of pure water, soil solids and air are insensitive to measurement frequency in the 10 to 1000 MHz range. However, any mixture of these may show dielectric dispersion (complex dielectric constant changes with frequency), especially if there are ions in the soil water (which is usually the case). For this reason the instrument response of low-frequency instruments, such as the CS615, is similar to that of TDR in soils with negligible K'' (Seyfried and Murdock, 2001, 2004). Temperature effects in these soils are dominated by the effect of temperature on pure water, for which the dielectric constant declines from 88 at 0 °C to 72 at 45 °C, which results in a slight negative temperature effect.

The imaginary component is related to soil solution ionic composition and concentration, properties of adsorbed ions and the degree of interaction between soil water and solids at the solid–liquid interface. These properties vary considerably with soil type. It appears that K'' is dominated by EC at the measurement frequencies of the CS615 (Campbell, 1990). The effect of EC on K'' is inversely proportional to the measurement frequency, so that TDR is less sensitive to individual soil properties than the CS615 and other low-frequency measurements and K^* tends to be greater when measured at low frequencies. In addition, EC is strongly temperature dependent. The EC of aqueous solutions increases about 2% per degree Celsius. The result is a strong positive temperature effect, which may be as great as that of soil water content, on all field soils we have measured.

Whereas field or laboratory calibration will generally give the best results for most soil moisture instruments, this process can be made efficient by understanding and generalizing either the overall sensor response or components of it so that the number of samples required can be minimized. Based on two sets of laboratory experiments, we provide a general calibration relationship that relates raw sensor output to a temperature-corrected soil water content. The approach requires independent measurements of

θ to determine the value of a single, soil-specific calibration parameter. It facilitates field calibration of the sensor because it requires relatively few measurements to determine the parameter value.

Materials and Methods

The results provided are based on two sets of experimental data. The first is that of Seyfried and Murdock (2001) from soils of the Reynolds Creek watershed in the USA and the second is a set of laboratory measurements for a variety of soils from Australia and New Zealand. Both studies used similar, but not identical, laboratory measurement approaches centred on measurements of the sensor response as a function of temperature and θ using repacked cores in the laboratory.

Seyfried and Murdock (2001) performed their measurements on four soil types: Sheep Creek, Summit, Foothill, and sand. The sand was construction sand rather than a natural soil. Table I provides sand and clay percentages, bulk density (from volumetric samples collected in the field) and EC measurements for these soils. Twelve soil horizons from seven soil types were included in the Australian and New Zealand soils measurements. Textures range from sand to heavy clay and all are natural soils. It should be

noted that the EC data provided by Seyfried and Murdock (2001) are measured on saturation paste extracts, whereas those for the Australian and New Zealand soils are measured on 1 : 5 (soil : water by mass) suspensions. The 1 : 5 dilution tests typically result in an EC that is substantially smaller than that obtained for saturation paste extracts (Slavich and Petterson, 1993). Nevertheless, the Australian and New Zealand soils have a lower EC (salinity) than the Reynolds Creek soils.

The response of CS615 output period to θ and soil temperature was measured for each soil using the following procedure. First, an appropriate mass of oven dry soil was thoroughly mixed with an appropriate volume of de-ionized water and packed into a PVC cylinder of known volume (Table II) to achieve a target bulk density (field value) and θ. The cylinder was then sealed to prevent changes in θ during the experiment. Bulk density and θ were determined gravimetrically after each set of measurements was completed. Target θ values were based on expected field values given the soil texture to achieve a wide range of θ while avoiding redistribution in the soil column during the experiment. The CS615 sensors and thermocouples for measuring the soil temperature were then inserted into the soil columns.

Table I. Soils used for laboratory calibrations

Country	Soil sample site and horizon (i.e. A or B horizon)	Sand (%)	Clay (%)	Bulk density (t m^{-3})	EC[a] (S m^{-1})
NZ	Carran's A	27	35	1·37	0·05
NZ	Carran's B	14	54	1·26	0·04
NZ	Clayden's A	18	43	1·21	0·05
NZ	Clayden's B	14	49	1·25	0·04
NZ	Satellite Station Hillslope A	22	27	1·55	0·03
NZ	Satellite Station Hillslope B	21	30	1·45	0·02
NZ	Satellite Station Valley A	8	59	1·03	0·06
NZ	Marine Rd A	16	56	1·12	0·05
NZ	Marine Rd B	17	53	1·13	0·03
Aust	Tarrawarra A	4	25	1·35	0·03
Aust	Tarrawarra B	3	50	1·5	0·02
Aust	Point Nepean A	99		1·47	0·02
USA	Foothill	31	29	1·5	0·145
USA	Sheep Creek	23	19	1·3	0·774
USA	Summit	69	5	1·7	0·25
USA	Sand	97	<0·1	1·52	0·00006

[a] Soil ECs were determined from natural samples using a 1 : 5 dilution test for Australian and New Zealand soils and using a saturation paste extract test for the USA soils. The bulk density is the *in situ* value.

Table II. Summary of experimental setup

	Reynolds Creek data	Australian and New Zealand data
Cylinder diameter (cm)	10·16	15·35
Cylinder length (cm)	33	33·5
Target temperatures (°C)	5, 15, 25,35, 45	5, 20, 25,35

The soil columns were allowed to come to thermal equilibrium in a controlled temperature chamber. Soil temperature and CS615 output period were then recorded using a data logger. Air temperature was changed progressively so that each target temperature (Table II) was attained and the measurements were repeated. Seyfried and Murdock (2001) measured three replicates for each θ combination. Only one replicate was used for each θ combination for the Australian and New Zealand soils, unless subsequent data analysis showed anomalies in either the temperature response or the θ calibration curve, in which case measurements were repeated to resolve the anomalous results.

Results

The results were analysed in two steps, starting with the behaviour for individual soils and then moving to developing generalized relationships. For the individual soils, the temperature effects were analysed first followed by the θ calibration relationship.
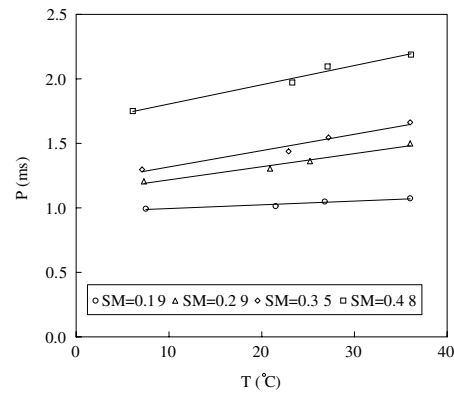

Figure 1. The effect of temperature on sensor output for four moisture contents for the Clayden A-horizon soil

The temperature response for each θ combination was determined by plotting the measured CS615 output period P_{obs} against measured soil temperature T. Typically, increasing T results in a roughly linear increase in P_{obs} with the slope increasing with θ (m^3 m^{-3}) (Figure 1). A linear regression was fitted to the P_{obs}, T data pairs for each soil–θ combination. The slope of the regression relationship C_T is effectively a temperature correction coefficient and can be used to calculate a P value corrected to 25 °C using

$$P_{25} = P_{obs} - C_T (T - 25) \qquad (2)$$

The second step was to examine relationships between θ and P_{25} (Figure 2). Clearly, there are marked differences in the calibration relationship
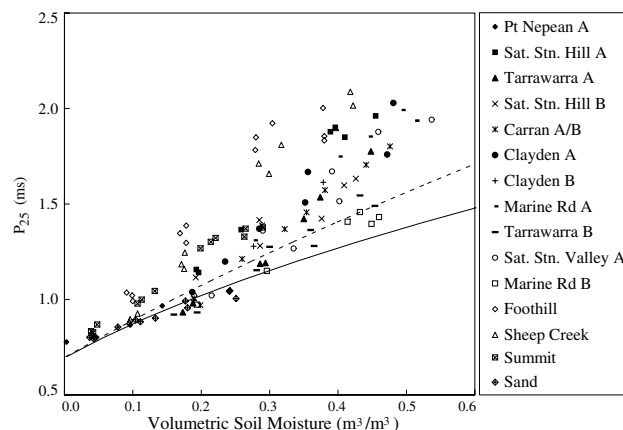

Figure 2. Comparison of measured volumetric soil moisture and the CS615 period at 25 °C. The manufacturer's calibration relationships for low EC (solid line) and 0·3 S m^{-1} EC (dashed line) soils are shown

between soils. Measured periods are smallest for the construction sand, intermediate for the soils from Australia and New Zealand, and greatest for the natural soils from Reynolds Creek for a given θ. This is in line with the general salinity (EC) levels increasing from the construction sand to the Australian and New Zealand soils, with the Reynolds Creek soils being the most saline. It is also clear that there is a general consistency between the two data sets in terms of the shapes and locations of the curves, which appear to form a family of relationships with a similar y-axis intercept. The spread in calibration relationships is much larger than suggested by the manufacturer.

Generalized Relationships

The next step was to develop generalized relationships for both the temperature dependence of the sensor and the $\theta - P_{25}$ calibration relationship. To collapse the θ response data (i.e. the family of relationships in Figure 2) onto a single curve, we calculate a normalized period N:

$$ N = \frac{P_{25} - P_{0.0}}{P_{0.4} - P_{0.0}} \qquad (3) $$

where $P_{0.0}$ and $P_{0.4}$ are the periods (temperature corrected to 25 °C) for θ of 0·0 m³ m⁻³ and 0·4 m³ m⁻³ respectively. This normalization was chosen because the relationships in Figure 2 appear to have similar y intercepts and shapes, but the curves appear to scale vertically relative to the intercept. Thus, choosing to scale the period responses relative to the intercept or zero moisture response and by the period response

over a fixed θ range should provide an efficient means of unifying the data. The value of $P_{0.0}$ is set equal to 0·76 ms, which is the average value observed by Seyfried and Murdock (2001) for oven-dry soil. $P_{0.4}$ is the free parameter that is set when applying the general calibration curve to a specific soil. We found that the power function relationship

$$ \theta = 0.4N^{\beta} \qquad (4) $$

is a good representation of the relationship between θ and N. The coefficient is set to 0·4 to be consistent with the definition of $P_{0.4}$.

To fit the combination of Equations (3) and (4), we jointly optimized β and $P_{0.4}$ using a nonlinear quasi-Newton optimization procedure with the objective of minimizing the sum of squared errors in estimated θ for all the experimental data simultaneously. This resulted in $\beta = 0.70$, which is taken as a constant applicable across all soils. Fitted values of $P_{0.4}$ for the experimental soils vary between 1·34 and 2·29, with an average of 1·69. Figure 3 shows the resulting relationship between normalized periods for each soil and θ, along with the generalized calibration curve. The root-mean-squared error (RMSE) of the θ estimate for this fit is 0·025 m³ m⁻³. It is worth noting that, while the q value chosen for the wet end of the normalisation (i.e. q = 0.4) is well above the largest q observed in many coarser textured soils, the general calibration curve still performs well for such soils (see Point Nepean and sand in Figure 3).

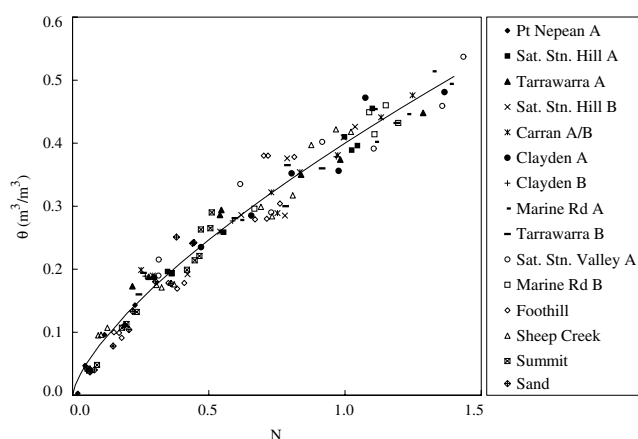In an attempt to generalize the observed relationships further, we analysed the relationships between

Figure 3. Comparison of normalized period N and volumetric soil moisture. The generalized calibration relationship is also shown

$P_{0.4}$ and soil texture, bulk density and EC. To make the EC measurements for the two data sets comparable, the $1:5$ dilution test results for the Australian and New Zealand data were multiplied by 6.4, as recommended by Lovejoy (1974). $P_{0.4}$ is weakly related to EC ($r^2 = 0.14$), clay content ($r^2 = 0.09$) and bulk density ($r^2 = 0.11$). If the two sandy soils are excluded, then these r^2 values improve to 0.27, 0.40 and 0.21 respectively. Only the clay content is statistically significant, and using the fitted relationship (to clay content) to predict $P_{0.4}$ resulted in a doubling of the RMSE to 0.049 m^3 m^{-3}. Using the mean of the fitted $P_{0.4}$ values resulted in a further degradation of the RMSE to 0.063 m^3 m^{-3}. On the basis of the current data set, it must be concluded that it is necessary to calibrate $P_{0.4}$ for each soil type.

Two other studies of the calibration of the CS615 water-content reflectometer shed some light on the generality of the calibration curves presented above. Stenger *et al.* (2005) studied four soil types with samples from three depths for each soil type. Comparison of their fitted curves with our generalized relationship suggests that our relationship is a close approximation for most of their soils. However, two gley soils stand out as having the opposite curvature and their Allophanic soil shows an inflection not captured either by our relationship or their quadratic fit. This indicates that caution needs to be taken when generalizing from our results. Kim and Benson (2002) studied a variety of soils from the USA. They used linear and quadratic calibration fits and found that the slope was strongly dependent on bulk soil EC, which is also consistent

with our data. Their data do not allow detailed comparison of calibration relationship shapes.

For the temperature correction, we use an approach where the raw sensor measurement is corrected prior to calculating θ. This is different to the approach taken by Seyfried and Murdock (2001) and also to that recommended by the sensor manufacturer (Campbell Scientific Inc., 1996), in that they both estimate a θ value that is then temperature corrected. We did this because it allows a general temperature correction determined from the raw sensor response to be estimated.

Figure 4 shows a strong linear relationship between C_T and P_{25}; however, the behaviour of the construction sand (which has an extremely low EC; see Table I) is clearly different from the natural soils. The negative slope apparent in the construction sand data indicates that the temperature effect is being dominated by the reduction in the real part of the dielectric constant of water with temperature. The positive slope for all other soils suggests that the temperature effect on soil EC (affecting the dielectric dispersion or imaginary component of the dielectric constant) dominates. The relationship between P_{25} and C_T is likely to arise from the strong links between these two parameters and the bulk soil EC (not necessarily the extract EC). Thus, both P_{25} and C_T respond as either the soil moisture or the soil specific properties influencing EC change, leading to the strong correlation observed. The solid line is the fit to all the data, excluding the construction sand ($r^2 = 0.89$). When combined with Equation (2), the fit to the overall data results in an
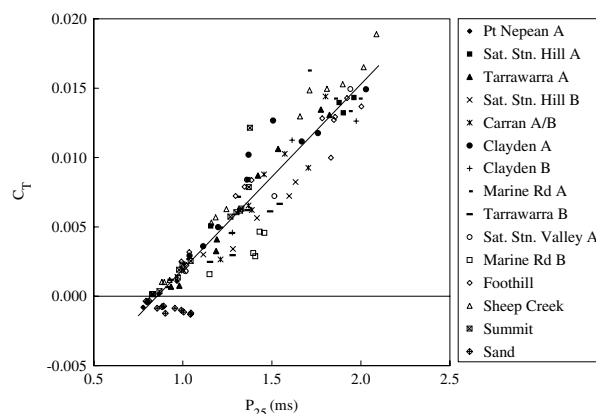

Figure 4. Comparison of the temperature correction coefficient and the CS615 signal at 25 °C. The fit to all the data (excluding the washed sand) is also shown (solid line)

empirical temperature correction equation:

$$P_{25} = \frac{P_{obs} + 0.0114(T - 25)}{1 + 0.0134(T - 25)} \qquad (5)$$

There is some difference between the fitted relationship and relationships evident for individual soils (Figure 4), as well as some scatter. To give an idea of the practical significance of the variation between the relationships we calculate the difference in estimated θ for a 10 °C temperature correction (from 15 to 25 °C) with the temperature correction calculated using linear regression fits to each soil individually and to the whole data set (solid line in Figure 4). Figure 5 shows this difference as a function of θ for all the soils. Two things are clear. First, the error introduced is small (generally less than 0.02 m³ m⁻³), compared with the practical accuracy expected in the field. Second, the error is a function of θ and changes rapidly and nonlinearly for small θ and then more gradually and linearly for greater θ.

It should be noted that C_T tends to be smaller for three soils: the B horizon soils for each of Tarrawarra, Satellite Station hillslopes and Marine Road. The reason for this is unclear.

Application to Field Measurements

The University of Melbourne is operating a soil moisture monitoring network in the Murrumbidgee basin as part of the Murray Darling Basin Water Balance Project, which is a GEWEX (Global Energy and Water Balance Experiment) catchment-scale experiment (Western *et al.*, 2002). To illustrate the application of the approaches described above we have compared field TDR measurements with CS615 measurements. The CS615 period measurements were temperature corrected to 25 °C using Equation (5) and the measured temperature. To calibrate the value of $P_{0.4}$ for each site and soil layer the first two available TDR measurements were used and the RMSE was minimized. Subsequent TDR measurements (5 and 6 at Adelong, 3 at Kyeamba) were used for validation. Figure 6 shows the validation TDR measurements of θ at three depths for two monitoring sites, along with the CS615 normalized periods. The general calibration curve (Equation (4)) is the solid line shown and it relates the normalized period to the predicted θ. Hence, vertical scatter about the curve shows the combination of the CS615 and TDR moisture measurement error. The RMSE for the validation points varies between 0.005 and 0.026 m³ m⁻³. There are only a small number of measurements at each soil depth, but they cover a reasonable range of θ and are independent of the measurements used to estimate $P_{0.4}$. It is apparent that the generalized calibration approach developed in this paper works well, with the residuals all being small and the shape of the general relationship fitting the data well.

Application Procedure

To apply the calibration procedure described above requires estimation of the $P_{0.4}$ parameter, which in turn requires:
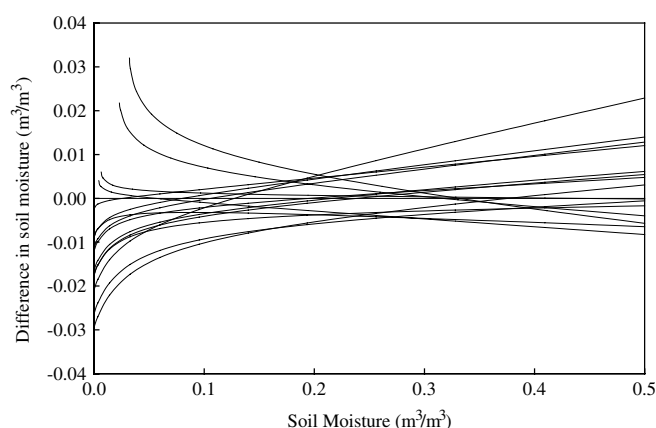

Figure 5. Difference between temperature-corrected (to 25 °C) soil moisture based on the fit to the data for each soil individually and the fit to all the data collectively (Figure 4) assuming a 15 °C measurement temperature
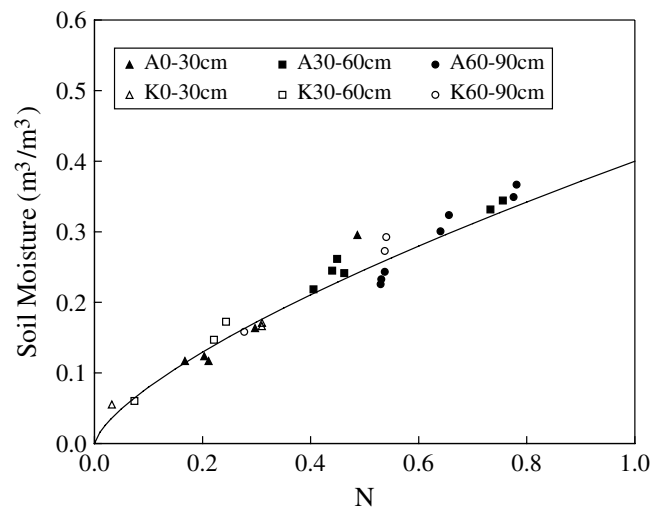
Figure 6. Comparison of CS615 normalized period N with TDR soil moisture estimates for Adelong and Kyeamba Creek soil moisture stations. $P_{0.4}$ has been optimized using these data. The solid line is the generalized calibration relationship (Equation (3))

1. Independent soil moisture measurements θ_{obs}. These will preferably be field measurements obtained using volumetric soil samples and gravimetric determination of bulk density and θ.
2. Corresponding measurements of CS615 period measurements P_{obs} and soil temperature T (probably from the monitoring record for the station).
3. Temperature correction of P_{obs} to P_{25} using Equation (5).
4. Finally, nonlinear optimization of $P_{0.4}$ to minimize the sum of squared differences between θ_{obs} and θ, where θ is obtained from the combination of Equations (3) and (4) with β set to 0·7 and $P_{0.0}$ set to 0·76 ms.

Although it is theoretically possible to estimate $P_{0.4}$ from one soil moisture measurement, we recommend an absolute minimum of three measurements spread across the whole operating soil moisture range for the monitoring site. This at least allows for some checking of residuals between the fitted calibration and the sample data to identify any issues with the samples or applicability of the calibration relationship. Once the value of $P_{0.4}$ is determined, the record of P_{obs} for the station can then be systematically temperature corrected (using Equation (5)) and converted to θ estimates (using Equations (3) and (4)).

Summary

Generalized temperature correction and soil-water calibration relationships for Campbell Scientific CS615 water-content reflectometer sensors have been developed and are described. To use the approach, measurements of soil temperature and the sensor output from the CS615 are required. In addition, several independent measurements of θ are required to set the one soil-related parameter in the θ calibration curve. This parameter (and thus the calibration relationship) is sensitive to soil characteristics, including EC, texture and bulk density. These vary between soils and over time (except texture). The between-soil variability is captured by variation in $P_{0.4}$. The temporal variability is a source of uncertainty in the measurement of θ. Although our data do not allow us to quantify this directly, our field applications (above and others) suggest that this is not a major source of error. With good-quality measurements, accuracy approaching that of TDR sensors can be achieved with this sensor. These relationships facilitate field calibration of these sensors to acceptable accuracies with only a small number of samples.

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